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MONOLITHIC $InP/Ga_{0.47}In_{0.53}As$ TANDEM SOLAR CELLS FOR SPACE

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ABSTRACT

This paper provides a review of progress made in the development of $InP/Ga_{0.47}In_{0.53}As$ monolithic tandem solar cells since the last SPRAT conference. Improved one-sun, three-terminal tandem designs have resulted in AM0 efficiencies as high as 23.9% at 25°C. Additionally, high-efficiency concentrator versions of the three-terminal device have been developed. The best concentrator tandem has a peak AM0 efficiency of 28.8% under 40.3 suns at 25°C. For the concentrator tandems, the subcell performance parameter temperature coefficients are reported as a function of the concentration ratio. Results from a computer modeling study are presented which provide a clear direction for improving the efficiency of the concentrator tandem. The prospects for fabricating high-efficiency, series-connected (i.e., two-terminal) $InP/Ga_{0.47}In_{0.53}As$ monolithic tandem cells are also discussed.

INTRODUCTION

During the last year, the monolithic $InP/Ga_{0.47}In_{0.53}As$ tandem solar cell has emerged as an attractive photovoltaic device for future space power applications. The device has several advantages for space applications over conventional GaAs-based tandems, (e.g., AlGaAs/GaAs and GaInP/GaAs), including a proven radiation-resistant InP top cell, an infrared-scavenging $Ga_{0.47}In_{0.53}As$ bottom cell and a high theoretical AM0 efficiency, particularly under concentration (ref. 1). Additionally, the tandem is based on a lattice-matched structure which is relatively easy to grow in high-quality form using a process such as metalorganic-vapor-phase epitaxy (MOVPE). A wide technology base for the $InP/Ga_{0.47}In_{0.53}As$ materials system has been established due to applications for these materials in other devices, (e.g., photodetectors and heterostructure bipolar transistors), thus allowing for rapid development of the $InP/Ga_{0.47}In_{0.53}As$ tandem cell.

Our first report on the $InP/Ga_{0.47}In_{0.53}As$ tandem cell was presented at the last SPRAT conference (ref. 1). At that time, we had fabricated the first working three-terminal prototype devices which had one-sun AM0 efficiencies of ~14% at 25°C. Since then, we have made considerable progress in several areas, including improved device designs, development of concentrator tandems with high AM0 efficiencies, evaluation of subcell parameter temperature coefficients and new computer modeling capabilities designed to identify key areas for improving the tandem cell performance. The purpose of this paper is to review the present status in each of the above-mentioned areas. Support for this work has been provided by the Naval Research Laboratory under interagency No. RU-11-W70-AD.

IMPROVED TANDEM CELL STRUCTURE

A schematic representation of the current $InP/Ga_{0.47}In_{0.53}As$ tandem solar cell structure is shown in figure 1. Note that the tandem utilizes three terminals; the middle contact is common to both the top and bottom subcells. In this preliminary work, we have constructed three-terminal devices in order to extract data from the component subcells more easily. Furthermore, in this configuration the subcells can be considered to be independently connected (i.e., much like mechanically stacked tandems). Details of the design and the functional aspects of the component layers in the structure have been described in an earlier publication, however there are two key differences between the current design and the prototype design reported previously (ref. 1). Firstly, a fully interdigitated top/middle contact grid metallization system is used on the latest generation of cells, which results in a square cell mesa geometry. Secondly, Entech prismatic covers are used on the cells to eliminate optical losses due to, 1) obscuration from the top/middle contact grids, and, 2) loss of top cell area due to the trenches required for placement of the middle contact grid. The light ray paths shown in figure 1 illustrate the effect of the Entech cover. Because of the effect of the cover, up to 20% of the cell surface can be covered with grid metallization. Additional details pertaining to the epitaxial growth and processing procedures for the tandem structure have been disclosed previously (ref. 1).

Both one-sun and concentrator tandem cells have been fabricated using this structure, however different cell areas, grid line specifications and Entech covers are used for each type of tandem. The one-sun cells have an area of 0.31 cm^2, grid lines which are 80-90 μm wide and 4-5 μm high and utilize Entech covers which are compatible with a grid line-to-grid line spacing of 508 μm. Since the concentrator tandems are designed to operate with much higher current densities, their cell area is reduced to ~0.065 cm^2 and Entech covers with lens elements spaced only 127 μm apart are used. Hence, the grid line width on the concentrator version is reduced to 20-25 μm in order to accomodate the tighter grid line spacing.

ONE-SUN TANDEM CELLS

A limited effort has been devoted to developing one-sun tandems, however, significant increases in efficiency have been realized using the improved structure described above. Illuminated current-voltage data for the most efficient one-sun tandem are shown in figure 2. The combined tandem efficiency is 23.9%. Higher quality structures have since been grown, however one-sun cells were not fabricated in these (see the results for the concentrator cells in the next section). With improved processing, one-sun, three-terminal cells with AM0 efficiencies of ~25% could be achieved. For the present cells, it is important to note the significant efficiency contribution from the $Ga_{0.47}In_{0.53}As$ bottom cell (5.6%). Note also that the subcell current densities are only mismatched by ~10%. Hence, it appears that high-efficiency, series-connected $InP/Ga_{0.47}In_{0.53}As$ tandem cells could be fabricated using a similar structure. For example, subcell current matching could be achieved by thinning the base layer of the InP top cell. Furthermore, suitable tunnel junctions in $Ga_{0.47}In_{0.53}As$ and lattice-matched GaInAsP (0.95 eV) have already been demonstrated (ref. 2), which could be easily incorporated into the present structure as an interconnect between the subcells. Assuming that the subcells could be current matched and a tunnel interconnect with minimal losses could be incorporated into the structure, a one-sun, two -terminal tandem

efficiency of >24% is predicted.

CONCENTRATOR TANDEM CELLS

The majority of effort in this project has been devoted to the development and characterization of concentrator versions of the tandem. The cell performance has been investigated as a function of the temperature and concentration ratio. The tandem efficiency data at 25°C under concentration are presented here and the subcell temperature coefficients are discussed in the next section.

Figure 3 shows AM0 efficiency data as a function of the concentration ratio for one of the better concentrator tandems. The $Ga_{0.47}In_{0.53}As$ bottom cell shows the expected increase in efficiency with concentration for a cell which is not series-resistance (R_s) limited. This behavior can be attributed to the thick lateral conduction layer above the bottom cell in the tandem structure which results in an extremely low effective emitter sheet resistance for the $Ga_{0.47}In_{0.53}As$ cell. In contrast, the InP top cell shows evidence of becoming series-resistance limited as the concentration ratio approaches 20. As the concentration ratio is further increased toward 100, the top cell efficiency behavior shows clear evidence of excessive R_s. This behavior is reflected in the tandem efficiency, which is the sum of the subcell efficiencies. The tandem shows a broad efficiency plateau with concentration and AM0 efficiencies ≥28% are observed from 10 to 60 suns. The high-R_s problem for the InP top cell is related to the high sheet resistance of the thin emitter layer coupled with aspects of the top cell grid design. Techniques for solving this problem are discussed in a section to follow on computer modeling.

Figure 4 gives current-voltage data for a three-terminal tandem at peak efficiency under concentration. The efficiencies of both subcells increase substantially under concentration, (compare with the one-sun data given in figure 2), particularly for the $Ga_{0.47}In_{0.53}As$ bottom cell, which adds a substantial contribution (8.1%) to the overall tandem efficiency (28.8%). Presently, the peak efficiency of the tandem occurs at relatively low concentration ratios and is limited by the high R_s of the InP top cell. As shown later, computer modeling studies and empirical studies predict that a small decrease, (as little as a factor of 4), in R_s for the top cell will allow the tandem to operate at a peak efficiency approaching 30% at ≥100 suns. Note, once again, from the data in figure 4 that the subcells are nearly current matched. Under the same assumptions used in the previous section, and using the open-circuit voltage data from figure 4 for each subcell, a series-connected concentrator tandem should have an efficiency ≥28% under 40 suns at 25°C.

CONCENTRATOR TANDEM SUBCELL TEMPERATURE COEFFICIENTS

Temperature coefficients (TC's) for each of the subcell performance parameters have been calculated as a function of the concentration ratio from measured current-voltage data. In the absence of excessive R_s, the TC's for the open-circuit voltage (V_{oc}) and fill factor (FF) should improve as the concentration ratio increases due to the logarithmic dependence of V_{oc} on the short-circuit current density. This effect is considered to be one of the advantages of operating under concentration. However, when excessive R_s is present, the TC for FF can actually worsen with increasing concentration.

These effects are illustrated in figures 5 and 6, which give the subcell TC's for V_{oc}, FF and efficiency, (each normalized to their values at 25°C), as a function of the concentration ratio. For the top cell data given in figure 5, the TC of V_{oc} is seen to improve with increasing concentration as expected, whereas the TC of FF degrades monotonically due to excessive R_s. The net effect is that the TC of efficiency remains relatively constant as a function of concentration. However, the data shown in figure 6 for the bottom cell is characteristic of what one would expect for a nearly ideal concentrator cell. There is no evidence of excessive R_s and the TC's for both V_{oc} and FF improve monotonically with the concentration ratio, resulting in a monotonic improvement in the TC of efficiency.

COMPUTER-MODELED TANDEM CELL PERFORMANCE

A computer modeling code has been developed which is designed to calculate the tandem cell performance as a function of *measured* subcell parameters and operational parameters such as the temperature and the concentration ratio. This capability has allowed us to study the previously mentioned R_s problem associated with the InP top cell in the concentrator tandem. Using the model, it is possible to track the effect on performance of reducing R_s and thereby set target values for R_s consistent with achieving a desired performance level under a given set of operating conditions. This approach has proven to be very useful as a means of identifying power loss mechanisms as well as avenues for maximizing the performance of existing device structures.

As mentioned above, the computer calculations are based on subcell parameters measured in the laboratory. Thus, the first step in this work involved obtaining the subcell device parameters as a function of temperature. Absolute external quantum efficiency (AEQE) data at 25°C and 80°C were obtained in order to calculate the illuminated short-circuit current density. These measurements showed that only the subcell band gaps changed with temperature, with the shape and level of the AEQE remaining constant. The magnitude of the subcell band gap temperature coefficients were determined from photoluminescence spectra obtained from actual tandem cell structures and taken at a series of temperatures from 20°C to 80°C.

Dark current-voltage (I-V) measurements of the subcells were performed over a similar range of temperatures and were then numerically fitted to obtain the temperature dependence of the diode quality factors, reverse-saturation current densities and series resistances. A computer model was then constructed to calculate the subcell efficiencies as a function of the temperature and concentration ratio. The model output was verified by comparing with measured one-sun subcell performance parameters. Precise agreement with measured open-circuit voltages was obtained by adjusting the reverse-saturation current densities by about a factor of two.

An analysis of the temperature-dependent dark I-V data revealed that R_s for the $Ga_{0.47}In_{0.53}As$ bottom cell was smaller than could be measured using the technique. A low, temperature-independent value of 6.4×10^{-5} ohm-cm^2 was therefore assumed. The InP top cell, however, had a value of R_s of 5.7×10^{-2} ohm-cm^2 at 25°C, which decreased linearly to 3.3×10^{-2} ohm-cm^2 as the temperature was raised to 80°C. Hence, as anticipated, R_s for the top cell was found to be large compared to the bottom cell. These values were then used in the computer model to predict the tandem cell performance over a range of temperatures and concentration ratios.

Figure 7 illustrates the utility of the computer model. In this figure, the modeled AM0 efficiencies for the bottom cell and the complete tandem, (i.e., top cell efficiency plus bottom cell efficiency), are plotted against the concentration ratio for temperatures ranging from 20°C to 80°C. In performing the efficiency calculations, the top and bottom subcells are assumed to be independently connected. The set of curves with solid lines in the figure give the modeled efficiencies using the measured subcell parameters. Note the close correspondence between the modeled data at 25°C in this figure and the measured data given in figure 3 for the same temperature. These results verify the accuracy of the model. In particular, the model correctly predicts the sharp drop in efficiency at high concentration ratios due to the high top cell series resistance. We have used the model to quantify the effect of reducing the series resistance of the InP top cell. The set of curves with dashed lines in figure 7 give the tandem efficiency when R_s of the top cell is reduced by a factor of 10 (i.e., from 5.7×10^{-2} ohm cm^2 to 5.7×10^{-3} ohm cm^2 at 25°C). The tandem efficiency shows a remarkable improvement at high concentration ratios for the lower value of R_s. In fact, AM0 efficiencies well in excess of 30% are predicted for concentration ratios greater than 100 at 25°C.

In a companion paper presented at this conference (ref. 3), we have shown that the top cell series resistance problem is caused by a high sheet resistance in the the thin emitter layer. The problem is easily solved by reducing the grid line spacing for the top cell metallization. At present, our concentrator cells are based on available Entech cover designs, which limits the smallest grid line spacing to 127 μm. This presents a barrier to further improvements in the performance of the present three-terminal tandem structure without resorting to more complicated metallization schemes (e.g., stacked, electrically isolated contacts). However, results from our work on single-junction InP concentrator cells (ref. 3) suggest that a series-connected version of the tandem, utilizing the grid design used on the single-junction concentrator cells, would experience its peak efficiency (~30% at 25°C) at ≥100 suns. Therefore, the prospect of fabricating high-efficiency, two-terminal InP/$Ga_{0.47}In_{0.53}As$ concentrator tandem cells, which utilize the current subcell device structures and off-the-shelf Entech covers, is very promising.

SUMMARY

The current status of InP/$Ga_{0.47}In_{0.53}As$ monolithic tandem solar cells has been reviewed. This new tandem cell combines several features which make it very attractive for high-efficiency space power applications. An improved three-terminal device structure has resulted in vastly improved one-sun and concentrator tandem cell efficiencies. One-sun AM0 efficiencies as high as 23.9% at 25°C have been achieved. Concentrator tandems have peak efficiencies of 28.8% under 40.3 suns at 25°C. The data gleaned from the work on three-terminal tandems has been used to demonstrate that high-efficiency, series-connected InP/$Ga_{0.47}In_{0.53}As$ monolithic tandems are possible with AM0 efficiencies ≥24% at one sun, and ≥28% under concentration. However, in order to attain higher tandem cell efficiencies at higher concentration ratios, R_s for the InP top cell must be reduced. This problem has also been shown to degrade the temperature performance of the top cell under concentration. Computer modeling and empirical studies suggest that concentrator tandem efficiencies approaching 30% should be possible through a reduction in R_s for the top cell.

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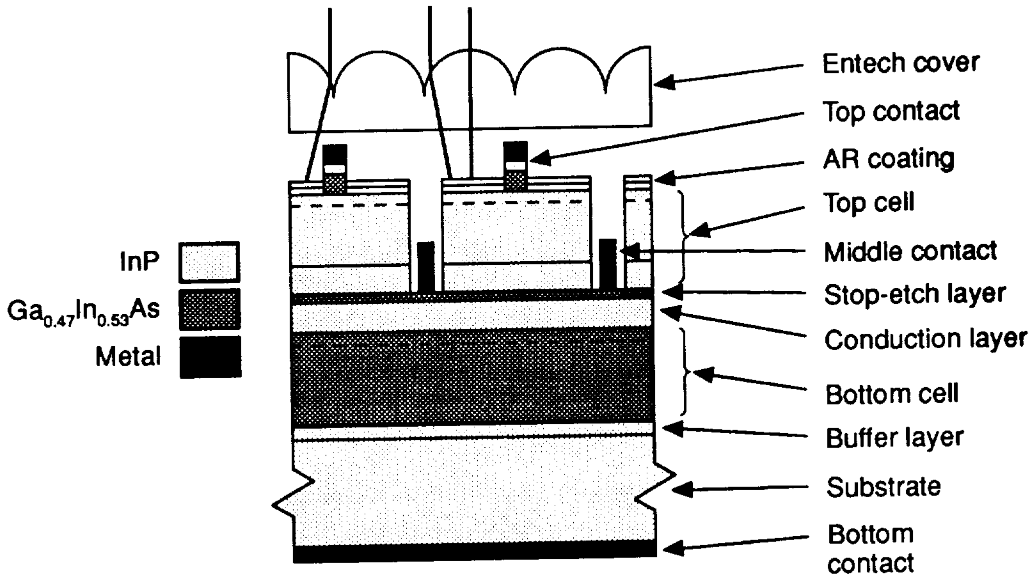

Figure 1. Schematic diagram of the three-terminal, monolithic $InP/Ga_{0.47}In_{0.53}As$ tandem solar cell structure.

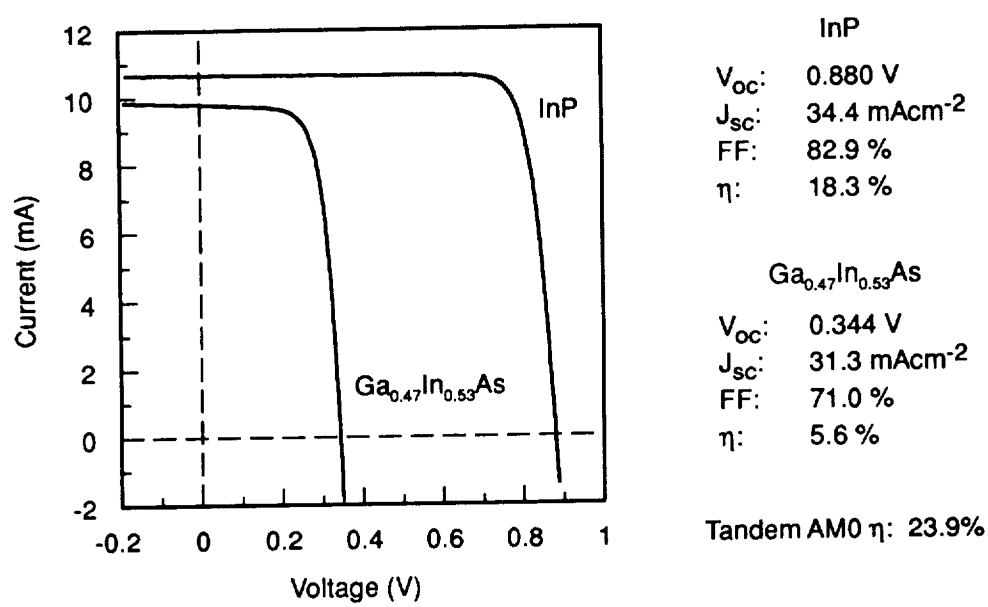

Figure 2. Composite one-sun current-voltage AM0-efficiency data for a high-efficiency, three-terminal, monolithic InP/ $Ga_{0.47}In_{0.53}As$ tandem solar cell at 25°C.

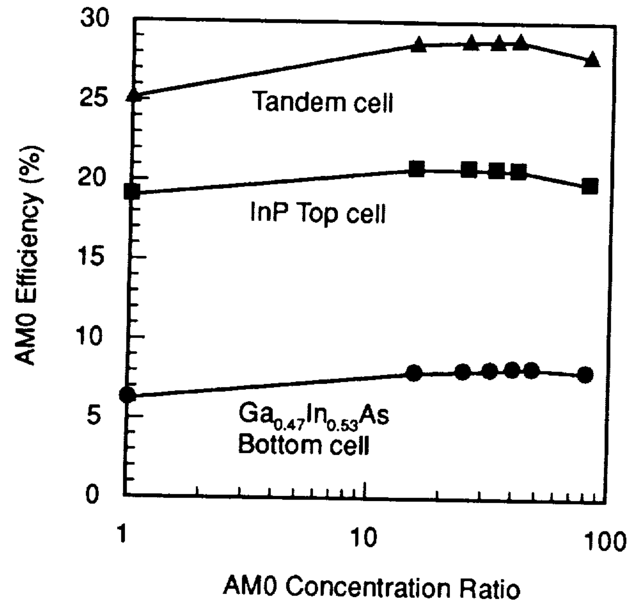

Figure 3. AM0 efficiency *versus* concentration ratio data for a high-efficiency, three-terminal, concentrator InP/ $Ga_{0.47}In_{0.53}As$ tandem solar cell at 25°C.

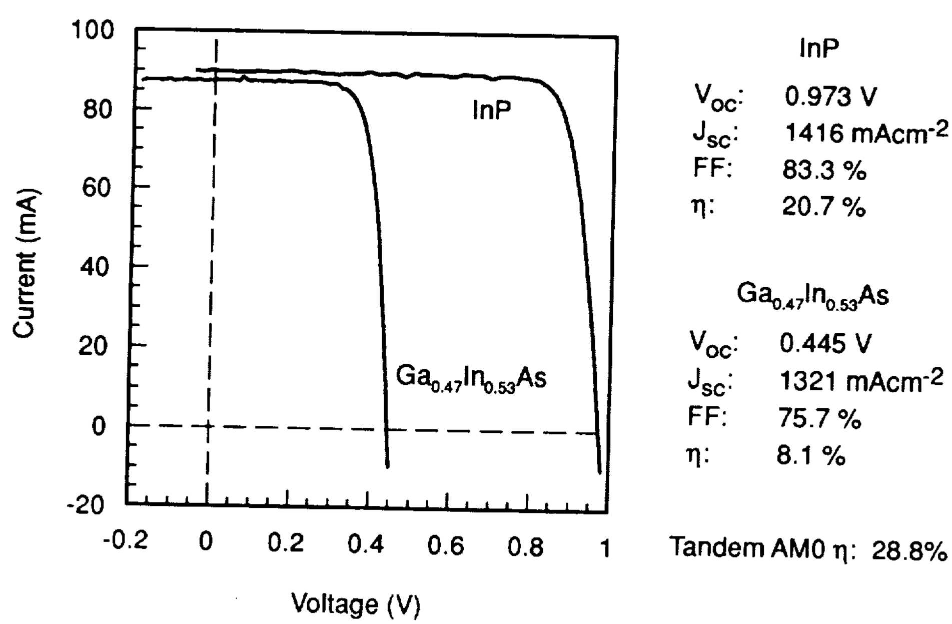

Figure 4. Composite current-voltage data for a three-terminal InP/$Ga_{0.47}In_{0.53}As$ tandem solar cell at peak AM0 efficiency under 40.3 suns concentration at 25°C.

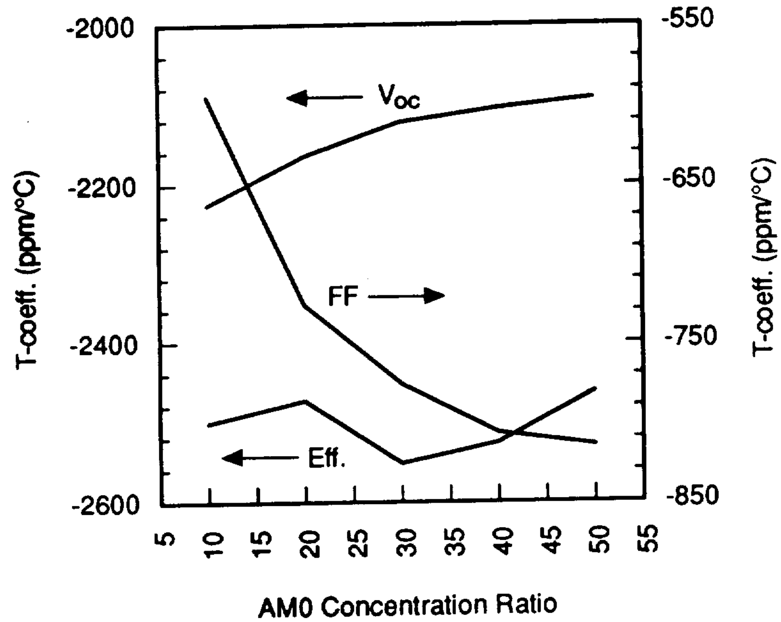

Figure 5. InP top cell performance parameter temperature coefficients as a function of the AM0 concentration ratio.

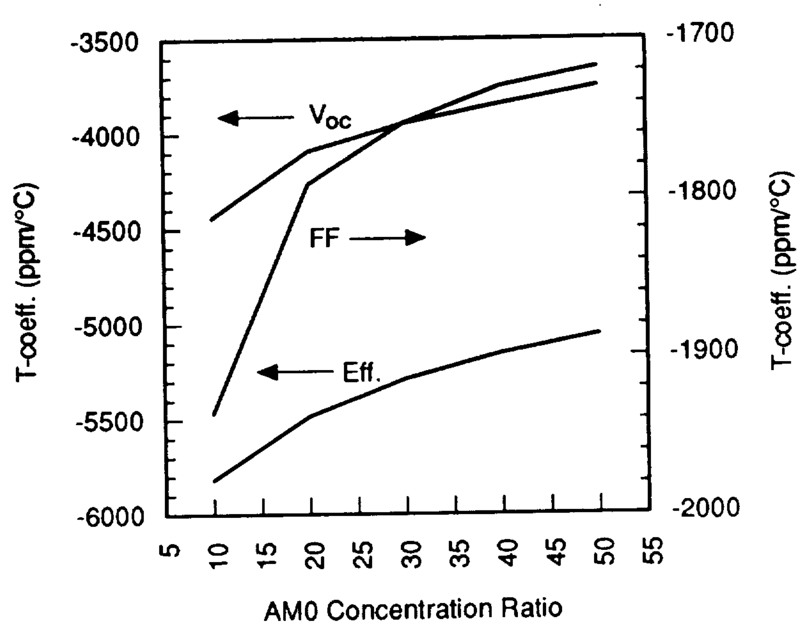

Figure 6. $Ga_{0.47}In_{0.53}As$ bottom cell performance parameter temperature coefficients *versus* AM0 concentration ratio.

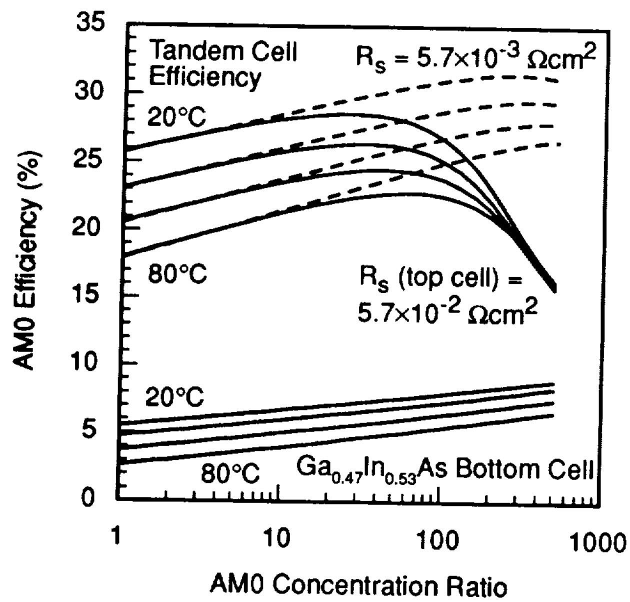

Figure 7. Modeled AM0 efficiency as a function of the concentration ratio and temperature for a three-terminal InP/ $Ga_{0.47}In_{0.53}As$ concentrator tandem cell based on measured subcell parameters. The dashed set of curves illustrate the effect of reducing the InP top cell series resistance by a factor of 10.